



Long-term chloride diffusion in silica fume concrete in harsh marine climates

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ABSTRACT

Supplementary cementitious materials such as silica fume are typically necessary for producing high performance concrete for marine environments in hot regions, such as the Persian Gulf. Silica fume use generally improves the strength and/or durability properties of the concrete. This paper investigates the effects of silica fume on various properties of concrete specimens that were exposed to Persian Gulf conditions. Samples were taken at the ages of 3, 9 and 36 months and analyzed to determine the chloride diffusion coefficient. The results show that partial cement replacement with up to 7.5% silica fume reduces the diffusion coefficient, whereas for higher replacement rates the diffusion coefficient does not decrease significantly. Also time-dependent chloride diffusion and compressive strength of concrete containing silica fume are investigated.

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1. Introduction

The Persian Gulf region is known to be one of the most aggressive environments for reinforced concrete constructions. Chloride-induced corrosion is believed to be the main reason for premature deterioration, and sometimes failure, of reinforced concrete structures constructed in this region [1–3]. The harsh climate of the Persian Gulf region can be described as having high temperatures, high evaporation rates and consequently high salinity of water, which increases the chloride induced reinforcement corrosion rates [4,5]. Typical extreme temperatures range from about 50 °C down to 3 °C and the relative humidity may be as high as 95% or as low as 5% [6].

The quality of concrete, mainly the permeability, nature and intensity of cracks, and the cover thickness, have a great bearing upon the initiation and sustenance of reinforcement corrosion [7]. Poor quality of concrete combined with aggressive environmental conditions has exposed inadequacies in design: some structures have had alarming degrees of degradation within less than a decade [8]. Application of supplementary cementitious materials (SCM) such as silica fume (SF) and fly ash (FA) to extend the service life of infrastructures has significantly increased in Iranian concrete practices of recent decades [9,10].

The SF is an efficient pozzolan that forms reaction products with the lime from hydrated cement and reduces the volume of large pores and capillaries found in cement paste. Consequently a more dense concrete is obtained. Neville [6] suggests a certain maximum

content of 8–10% of cementitious materials for SF content in the Persian Gulf region. As using silica fume induces a tendency for plastic shrinkage in concrete, precautions should be taken to avoid early moisture loss and any ensuing cracking [11].

This paper presents the results of an extensive experiment carried out as a part of a contract with Iran's Management and Planning Organization to develop a new service life design model for durability-based design in the Persian Gulf, which would provide a more realistic prediction of corrosion initiation for RC structures in this region [12]. This model is based on the results obtained from a complete set of field investigations on chloride diffusion, and considers parameters such as water to cement ratio, silica fume content, curing condition, exposure condition, environment temperature and surface coating. Detailed information on the project can be found elsewhere [13,14].

The results of investigations on the long-term effects of silica fume and water to cementitious materials ratio on durability performance of concrete exposed to the tidal zone of Persian Gulf environment are presented. Moreover, the decrease in the diffusion coefficient with time and improvement in compressive strength of concrete are studied.

2. Experimental program

2.1. Materials

The cementitious materials used in this study were Portland cement (PC) equivalent to ASTM Type II, and silica fume (SF) obtained from Azna ferro-silicon alloy manufacture. The chemical and physical properties of these materials are given in Table 1. The

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Table 1
Chemical and physical properties of portland cement and silica fume.

	Cement	Silica fume
<i>Physical tests</i>		
Specific surface, blaine (m ² /kg)	290	
Initial setting time (min)	145	
Final setting time (min)	210	
Compressive strength of 50 mm cube (MPa)	3-day	18
	7-day	29
	28-day	40
		–
Autoclave expansion (%)	0.2	
<i>Chemical analyzes (%)</i>		
Silicon dioxide (SiO ₂)	20.03	93.16
Aluminum oxide (Al ₂ O ₃)	4.53	1.13
Ferric oxide (Fe ₂ O ₃)	3.63	0.72
Calcium oxide (CaO)	60.25	–
Magnesium oxide (MgO)	3.42	1.6
Sodium oxide (Na ₂ O)	–	–
Potassium oxide (K ₂ O)	–	–
Sulfur trioxide (SO ₃)	2.23	0.05
Loss on ignition	1.37	1.58
<i>Bogue potential compound composition (%)</i>		
Tricalcium silicate C ₃ S	49.9	
Dicalcium silicate C ₂ S	23.5	
Tricalcium aluminate C ₃ A	6.6	
Tetracalcium aluminoferrite C ₄ AF	10.9	

aggregates used were crushed limestone from Metosak plant and were graded according to ASTM C 33 [15]. The coarse aggregate had maximum size of 12.5 mm and specific gravity and absorption values of 2.79% and 1.9%, respectively. The fine aggregate had specific gravity and absorption values of 2.59% and 3.2%, respectively. The fineness modulus of fine aggregates was 3.2. Polycarboxylate ether polymer superplasticizer and lignosulphonate plasticizer were used for the mixes in order to improve the workability of fresh concrete.

2.2. Mixture proportions

Four separate series of concrete mixes were developed at the water to cementitious ratios of 0.35, 0.40, 0.45 and 0.50. All series

included four SF mixes with 5%, 7.5%, 10% and 12.5% silica fume and the control mix without any SF. All series were proportioned to have the same total cementitious materials content of approximately 400 kg/m³ which is typical of those used in the marine concrete structures in Iran. The details of the concrete mixtures are given in Table 2.

2.3. Specimen preparation, casting and curing

The concrete mixtures were prepared in the laboratory of the Construction Materials Institute at the University of Tehran using a 0.1 m³ countercurrent pan mixer. The freshly mixed concrete was tested for air content according to ASTM C 231 [16], pressure method; slump according to ASTM C 143 [17]; and unit weight in accordance with ASTM C 138 [18]. Properties of fresh concrete are summarized in Table 3. Cubes of 150 × 150 × 150 mm and prisms of 150 × 150 × 600 mm in dimension were cast in steel mold and compacted on a vibrating table. The 150 mm cubes were used for the determination of compressive strength while the prisms were used to test chloride diffusion. The molds were covered with burlap kept wet for 24 h after casting. The specimens were removed from the molds and were allowed to cure in water saturated with calcium hydroxide at 21 °C for 28 days. After the curing period the prism specimens were sealed on four sides using epoxy polyurethane coating to ensure one-dimensional diffusion as illustrated in Fig. 1.

2.4. Exposure condition

The specimens were moved to an investigation site located in Bandar-Abbas, Iran and were continuously subjected to tidal zone exposure condition in Persian Gulf (Fig. 2) for the entire period of investigations (36 months). Exposure site is situated at the general water levels of low tide periods, so that specimens are exposed to atmosphere for about 2 h, simulating the tidal zone condition. Due to the location of the site and the specimen dimensions, no significant drying occurs.

The Gulf water is highly saline due to its enclosed condition (mostly surrounded by lands of Iran and Arabian Peninsula) and the high evaporation rate. Chemical analysis of the sea water is

Table 2
Details of the concrete mixtures.

Series	Code	w/cm	SF (%)	Water (kg/m ³)	Binder (kg/m ³)		Fine aggregates (kg/m ³)	Coarse aggregates (kg/m ³)	Superplasticizer (kg/m ³)
					Cement	SF			
1	SF0W1	0.35	0	140	400	–	936	973	7.2
	SF1W1	0.35	5	140	380	20	931	968	–
	SF2W1	0.35	7.5	140	370	30	931	968	6.0
	SF3W1	0.35	10	140	360	40	906	968	6.4
	SF4W1	0.35	12.5	140	350	50	929	964	4.8
2	SF0W2	0.40	0	160	400	–	836	1022	2.2
	SF1W2	0.40	5	160	380	20	833	1018	3.6
	SF2W2	0.40	7.5	160	370	30	832	1017	3.2
	SF3W2	0.40	10	160	360	40	830	1014	3.6
	SF4W2	0.40	12.5	160	350	50	829	1012	3.8
3	SF0W3	0.45	0	180	400	–	815	997	2.4*
	SF1W3	0.45	5	180	380	20	810	990	1.2
	SF2W3	0.45	7.5	180	370	30	808	998	2.0
	SF3W3	0.45	10	180	360	40	807	985	1.8
	SF4W3	0.45	12.5	180	350	50	806	983	2.0
4	SF0W4	0.50	0	200	400	–	778	956	1.2
	SF1W4	0.50	5	200	380	20	793	991	0.8
	SF2W4	0.50	7.5	200	370	30	784	959	1.2
	SF3W4	0.50	10	200	360	40	820	1020	1.8
	SF4W4	0.50	12.5	200	350	50	782	955	2.0

* In this mix lignosulphonate plasticizer was used instead of polycarboxylate ether polymer superplasticizer.

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